AUTONOMOUS COMMAND OPERATIONS OF THE WIRE SPACECRAFT

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Abstract

This paper presents the end-to-end design architecture for an autonomous commanding capability to be used on the Wide Field Infrared Explorer (WIRE) mission for the uplink of command loads during unattended station contacts. The WIRE mission is the fifth and final mission of NASA's Goddard Space Flight Center Small Explorer (SMEX) series to be launched in March of 1999. Its primary mission is the targeting of deep space fields using an ultra-cooled infrared telescope. Due to its mission design WIRE command loads are large (approximately 40 Kbytes per 24 hours) and must be performed daily. To reduce the cost of mission operations support that would be required in order to uplink command loads, the WIRE Flight Operations Team has implemented an autonomous command loading capability. This capability allows completely unattended operations over a typical two-day weekend period. The key factors driving design and implementation of this capability were:

1) Integration with already existing ground system autonomous capabilities and systems,
2) The desire to evolve autonomous operations capabilities based upon previous SMEX operations experience – specifically the SWAS mission,
3) Integration with ground station operations both autonomous and man-tended,
4) Low cost and quick implementation, and
5) End-to-end system robustness.

A trade-off study was performed to examine these factors in light of the low-cost, higher-risk SMEX mission philosophy. The study concluded that a STOL (Spacecraft Test and Operations Language) based script, highly integrated with other scripts used to perform autonomous operations, was best suited given the budget and goals of the mission. Each of these factors is discussed in addition to use of the SWAS mission as a testbed for autonomous commanding prior to implementation on WIRE. The capabilities implemented on the WIRE mission are an example of a low-cost, robust, and efficient method for autonomous command loading when implemented with other autonomous features of the ground system. They can be used as a design and implementation template by other missions interested in evolving toward autonomous and lower cost operations.

Keywords: Automation, satellite operations, low-cost operations

Abbreviations: AOS: Acquisition of Signal; ATS: Automatic Time Sequence; CCSDS: Consultative Committee for Space Data Systems; COP: Command Operation Procedure; FARM: Frame Acceptance Reporting Mechanism; FAST: Fast Auroral Snapshot Telemeter; FOP: Frame Operation Procedure; FOT: Flight Operations Team; FTP: File Transfer Protocol; GSFC: Goddard Space Flight Center; I&T: Integration and Test; ITOS: the Integrated Test and Operations System; LOS: Loss of Signal; MOC: Mission Operations Center; NASA National Aeronautics and Space Administration; PC: Personal Computer; SAMPEX: Solar Anomalous Particle Explorer; SERS: Spacecraft Emergency Response System; SMEX: Small Explorer; STOL: Spacecraft Test and Operations Language; SWAS: Sub-Millimeter Wave Astronomy Satellite; TCP/IP: Transmission Control Protocol/Internet Protocol; TPOCC: Transportable Payload Operations Control Center; TRACE: Transition Region and Coronal Explorer; UDP/IP: Uniform Data Packet Internet Protocol; WIRE: Wide Angle Infrared Explorer

1. Introduction

The SMEX missions have historically been leaders for new operational and architectural ground system philosophies at the Goddard Space Flight Center. The fundamental philosophy for the SMEX Flight Operations Team is the multi-mission operations concept. This concept was developed by the FOT, which had one team responsible for all of the SMEX spacecraft. These spacecraft currently include: SAMPEX, FAST, TRACE, and SWAS , which have all already launched and are operational. Also included in the SMEX series is WIRE , which is scheduled to launch in February of 1999. The multi-mission concept is effective because the SMEX FOT is involved in all aspects of a mission development and on-orbit operations. A portion of the team works in the pre-mission phase of a mission that includes integration and testing and developing the operational concept for a mission. Beside their main tasks in the pre-mission phase, a secondary task is to transfer the knowledge back to the core team that will eventually take on the routine operation responsibilities.

2. SMEX Operational history

SAMPEX used the Transportable Payload Operational Control Center for its ground system, and was the first major GSFC mission to migrate away from a traditional mainframe ground system. TPOCC used a workstation-based system that provided the mission with a high degree of flexibility for the time. Data servers with additional workstation strings could be added for operational support during high activity periods, such as the launch and early orbit phase. The operational philosophy still reflected a traditional operational approach whereas the flight team and the I&T teams were two separate teams and different ground systems were used for I&T and ops. At launch, the ops team still supported seven days a week, 24 hours a day. Although the ground system architecture was beginning to evolve, little improvement had been made to the operational concept.

After the launch of SAMPEX in July 1992, the SMEX FOT developed the first step in automating operations and reducing costs for the mission. The concept of "blind passes" was created and tested. The concept allowed the SMEX FOT to staff the control center seven days a week, but only 16 hours a day. During the remaining eight hours, the spacecraft was commanded from the stored command load. The on-board command load allowed the spacecraft to dump its science data to the ground during the supports without any intervention from the ground. The FOT configured the spacecraft to dump the data three minutes after AOS, which allowed the ground station personnel time to account for station masking or acquisition problems. After this concept was tested, both the SMEX FOT and NASA gained confidence, and staffing was further reduced to 12 hours a day, seven days a week.

Because of problems with the launch vehicle, FAST launch operations were twice ordered to stand down. After the second FAST stand-down in October 1995, a 25% FOT staff reduction was needed to reduce the overall budget for SMEX. The team's staff was reduced from 20 people to 15. When the reduction occurred, SMEX still only had one spacecraft in orbit, but the reduction forced the team to examine the routine operations work and eliminate or reduce the amount of work that was required daily.

Although the ground system architecture remained relatively similar to the SAMPEX mission, the FAST team began to incorporate new and more effective operational strategies. The first change started in the pre-mission phase when the ops team was integrated into the I&T team. Although an integrated team is standard practice for most missions today, at the time it was a new direction for GSFC missions. Changes also were incorporated into the ops concept. Once FAST launched in August 1996, the SMEX team began multi-mission operations. Because of the use of blind passes, and with FAST transitioning to routine operations, the control center staffing was able to be reduced from 12 hours a day to 8 hours a day. In October 1997, the SMEX FOT started five-day operations. The control center was only staffed Monday through Friday, 8 hours each day. To meet this level of reduced staff coverage, several other tools had to be incorporated. The use of blind passes was still being used during the SMEX FOT off-hours.

One of the problems in going to five-day operations was preventing the spacecraft watchdog timer from timing out. On all SMEX spacecraft, a watchdog timer monitors the time receipt between ground commands. If this time between commands exceeds 24 to 28 hours (dependent on which mission), the spacecraft will re-boot itself causing an impact to the science mission and requiring one to several days to fully recover the satellite. A method was developed that allowed the ground station personnel at Wallops Flight Facility to uplink no-operation commands from a file during normal supports when the SMEX FOT was not staffing the control center. The no-operation commands were uplinked on every blind pass that Wallops ground station supported. This procedure proved effective and reliable. Since the start of five days operations, none of the spacecraft watchdog timers have ever caused a spacecraft re-boot.

A second problem that was encountered for five-day operations was weekend on-board command loads. The on-board command load had to be increased from 24-hour coverage to 48-hour or 72 hour coverage to preclude the need for uplinking command loads to the spacecraft on Saturday or Sunday. The SMEX FOT looked at several activities and command sequences in the stored command load and was able to reduce or eliminate some of the commands in the loads. This reduction allowed the on-board command loads to cover 48 or 72 hours and two loads were uplinked to control the spacecraft over the weekend. To reduce the risk to the spacecraft and prevent large amounts of data loss, other elements in the end-to-end data flow were augmented. Arrangements were made with the ground stations and data processing teams to contact the flight ops team if a problem from a pre-defined list occurred. Since the start of the five-day operations, science data capture has not declined and remains above 99% for all SMEX missions and no spacecraft anomalies have caused any serious problems because of the reduced staff coverage.

With the launch of TRACE in April 1998, the FOT incorporated the same five-day operation concept for its normal operations. The TRACE team added new tools for monitoring the spacecraft. The SERS was created by NASA to help monitor spacecraft. SERS scans through the system event logs looking for anomalous events or violations or any other messages that the flight operations define. If an anomalous event or violation is found, the system will notify the SMEX FOT by email and pages. A list of team members is notified until an acknowledgement is received back to SERS from the pager. This system allowed the SMEX FOT to gain more confidence and insight into the health and safety of the spacecraft during off-hours. Because of the success of the system SWAS has started to use it after launching in December 1998. WIRE is currently being configured on the system and FAST will start using the system in early 1999.

The ground system also underwent significant architectural changes. For SAMPEX and FAST, the ground system was based on workstations with separate front-end processors. TRACE used the ITOS system for its ground system. This system incorporated the front-end processor functions into the workstation thus requiring only one unit. The ITOS ground system also was the main ground system for all of SMEX I&T. Therefore the FOT developed many of the pages and procedures during the I&T phase, which allowed the FOT to re-use most of them for operations. Additionally, the ITOS system was hosted onto desktop and laptop PC's in addition to workstations for added flexibility. Although workstations were used primarily for the TRACE control center, much less expensive desktop and laptop PC's could now be used for high activity periods for added cost savings. The FOT used the laptop PC's for procedure and documentation development in their office or even at home, and then easily integrated the changes into the system.

Unique problems arose with the SWAS and WIRE operations plans. The time-lines in the on-board command load are numerous because it gives several targets for the spacecraft to investigate. Because of their large size, the command loads time period could not be extended to cover the entire weekend. For these two missions to meet the current five-day operations concept and to maintain the same level of science data collection, the SMEX FOT developed and created an autonomous command load procedure that uses STOL language and UNIX scripts. The ground system architecture and spacecraft command concepts used for autonomous commanding will be discussed in the following sections.

3. Autonomous Architecture Overview

The current capabilities developed for autonomous operations are in the support of autonomous station contacts, which are referred to as blind passes. These are performed using virtually the same processes as tended supports except that automation tools perform system configurations, receipt and monitoring of data, and post-pass processing of pre-recorded housekeeping and science data in place of flight team personnel. During all normal contacts the WIRE Spacecraft autonomously transmits real-time housekeeping telemetry, dumps stored housekeeping , and science telemetry data. Normal contacts are pre-scheduled contact times of approximately 8-10 minutes duration and occur 3 times daily. All telemetry management, transmitter ON/OFF, and other spacecraft management functions related to supporting normal contacts are performed via onboard stored commanding (i.e. a command load or ATS load).

The ITOS ground system Mission Operations Center or MOC autonomously performs self configurations to support the contact as would be done by flight team personnel, and configures TCP/IP and UDP/IP network connections as a server. The ground station initiates port connections as the client. The connections are normally performed manually by station personnel but may also be performed autonomously if the station is also un-tended. ITOS receives real-time data during the contact and stored housekeeping data post-contact via FTP. Recorded science data is FTP'd directly to the science team post-contact. The MOC processes both real-time and post-contact data to look for anomalous spacecraft conditions. Flight team members are notified via pager of any such conditions.

The current capabilities, as described in the above overview, have been further developed to also provide for autonomous commanding of the spacecraft. The following sections describe the basic tools of the ground system that are used to provide this capability and how they have been adapted to support command loading for the WIRE mission.

4. Key Components: ITOS, SERS, UNIX Scripts

The core tools and features of the MOC needed to support autonomous operations consist of the ITOS, SERS (Spacecraft Emergency Response System), and Unix/Solaris scripts. The role of each is discussed below.

ITOS

ITOS is a workstation based software package developed in-house at GSFC that runs under the SUN/Solaris operating system. ITOS provides many features but its key capabilities for the support of autonomous operations are:

- STOL (System Test and Operations Language) procedural scripting
- Limit and configuration monitoring of telemetry
- Event capturing and logging
- Telemetry archival and replay

Time based execution of STOL procedures drive the configuration and setup for station contacts, the real-time data processing and commanding during a contact, and the post-pass processing of stored housekeeping data. The procedures used to support autonomous operations (i.e. the blind pass procedures) are highly enhanced variations of scripts used to perform the same basic functions during a flight team tended contact.

ITOS provides a limit and configuration monitoring capability of spacecraft telemetry that is configured to create 'event messages' whenever a telemetry point is not within an expected range or not set to an expected discrete value. Other messages are generated from ITOS system events, the status of telemetry and command processing, and the execution of STOL and Unix scripts. All such events are written to an event log and are created for both real-time and post-pass playback data.

SERS

The SERS system was developed out of a general drive to reduce operations costs by reducing flight team personnel support requirements. It was first implemented on the TRACE mission and will be used on all other SMEX missions except SAMPEX. The SERS system is instrumental for ensuring automation robustness. It notifies flight team personnel of the occurrence of any anomalous conditions including the failure of the STOL scripts themselves to complete command loads and other activities. It performs this function via processing of event logs (real-time and post-pass) created from the contact. Each log file is opened and read for limit, configuration, and ITOS system event messages that are considered anomalous. All such messages are then transmitted to several flight team personnel, who are designated as being on call during the support. The flight team member receiving the SERS alert must use his/her pager to acknowledge receipt or the system will alert the next member in the list. All event messages appear on the pager display in full format and length as they would be read from the workstation console. After reviewing the message(s) the FOT member can then decide what action, if any is necessary.

Unix/Solaris Scripts

Unix scripts are used to perform various cleanup activities including moving files between workstations and within directories of a workstation. Examples of this include the automatic transfer of event log files from the prime and backup workstations to the SERS, the transfer of attitude and orbit files (created from post-pass playback of housekeeping data) to the flight dynamics support system, and the transfer of housekeeping data to the data processing system. As data is moved to its final destination and/or archival location(s) it is deleted from intermediate storage directories. All ground system elements are networked and all file transfers are performed via FTP. A key UNIX script was developed for the Auto-Commanding procedure that monitors the

ITOS software. If the software processes gets killed or hung, the script will perform a system reboot and re-configure the software. This allows the flight ops team to have confidence that science data loss or a failure in the uplink of a store command load will not be due to mission software failure on ITOS.

5. Spacecraft Command Concepts

Multi-layered command protocol

To effectively perform autonomous spacecraft commanding, ITOS STOL procedures were modified to include a thorough verification of successful load completion. This verification is based upon the combined spacecraft and ground system command verification protocol.

Commanding and command verification for the WIRE spacecraft are identical to the other SMEX spacecraft and relies upon a multi-layer command protocol based upon CCSDS COP-1. The ITOS system implements the FOP and the spacecraft implements the FARM in its command ingest software. In addition, the system performs command verification via a software task monitoring the command counter and end-item verification. End-item verification is accomplished by monitoring the telemetry for spacecraft configuration changes. For both tended and autonomous operations, the STOL procedures make extensive use of both software command counter checks and end-item verification. The COP-1 command verification is automatically performed in the background for all commands. The successful or unsuccessful history of all commanding is reported in the ITOS event log.

Command Load Uplink

The WIRE mission requires that two command loads be uplinked to the spacecraft daily. Each load contains spacecraft management, instrument configuration, and spacecraft maneuver commands covering a twelve-hour duration with approximate size of 18 Kbytes. The two loads together span 24 hours of operation. Uplink for the command load set is performed during a single station contact of 8-10 minute duration and requires 4-6 minutes of uplink time. The load set is uplinked approximately 18 hours prior to the current set expiring.

If the load attempt fails, the flight team will have one already normally scheduled pass (at approximately12 hours prior to the current onboard load set expiring) during which another attempt can be made. Additional station contacts can also be scheduled as needed. In the worse case scenario, several attempts at loading would fail resulting in the current onboard command load expiring. The result would be the spacecraft entering a safing mode. The FOT would then execute an easy transition back to science mode by completing the command load and re-starting the load processing. Although this is benign from the spacecraft operations standpoint, it is highly undesirable from the overall mission standpoint due to the shortness of the mission. (The WIRE nominal science mission will only last four months because of the evaporation of the on-board cryogen). Thus, it is actually more important that flight team personnel are notified of a load failure than the failure occurring itself. This is true since there will typically be plenty of time to complete the loading operation manually in a subsequent contact. The importance of the SERS system as a cornerstone to any autonomous operations can be readily seen. Information that the autonomous loading operation has failed is passed to the SERS via the blind pass procedure writing a specific ‘failure’ message into the ITOS event log. The details of the loading process are best understood by examining the flow of the blind pass procedures as discussed in the next section.

6. Autonomous Operations with Command Loading

The WIRE mission uses three main STOL procedures to perform blind pass operations. Two of these are executed on the prime workstation and the other on the backup workstation. Several Unix scripts are called from these procedures, some of which transfer the event log files to the SERS. The SERS is always running and notifies the FOT when anomalous conditions are observed.

Prime Workstation functions:

The prime workstation is the only workstation actively involved in taking the pass and acts as the command and telemetry interface to the spacecraft through the ground station. It performs telemetry and limit configuration monitoring, archives all real-time data received during a contact, maintains the event log, and performs the command loading to the spacecraft.

1. "Auto Load" Procedure

This is the first procedure run and is executed manually by the flight team. Its basic function is to allow the selection of command load file names and their allowable uplink times. Command load file names are read from a directory where they are then stored into a separate 'loadlist' file for later manipulation. The flight team member executing the procedure selects the desired uplink time from those available for each load file. The procedure then stores this information into the 'loadlist' file for later use.

2. "Ground Configuration" Procedure

This procedure is called from the "Auto Load" procedure and performs all pre-pass configurations, real-time pass activities, and post-pass cleanup activities. The first job of the procedure is to read in the station support schedule and select the passes for the WIRE mission. This is necessary since the schedule contains station contacts for all of the SMEX missions. Next it opens and reads the 'loadlist' file and determines which loads will be uplinked in which pass. The procedure performs this by comparing the uplink times selected previously with the pass AOS/LOS times from the support schedule just read. A page display is created summarizing pass times, station, orbit, and the load files to be uplinked.

The procedure then waits until 30 minutes prior to the acquisition of the spacecraft telemetry (AOS –30 minutes) at which time it resumes its execution and performs the final configurations for taking the pass (Fig 1). This includes opening and closing command and telemetry ports, opening archive and event log files, turning on limit and configuration checking, and opening attitude and orbit archive files. Additionally, the procedure determines which two load files are to be uplinked during the pass.

At AOS-10 minutes connections with the station are formed and the procedure waits for AOS. During the pass the two loads are uplinked. The procedure performs load confirmation by looking for end-item verification of the load counter from the two spacecraft flight software tasks involved in the loading process. The two verification parameters are checked and if either indicates the loading was unsuccessful then the attempt is marked as failed. This prevents the procedure from suspending while

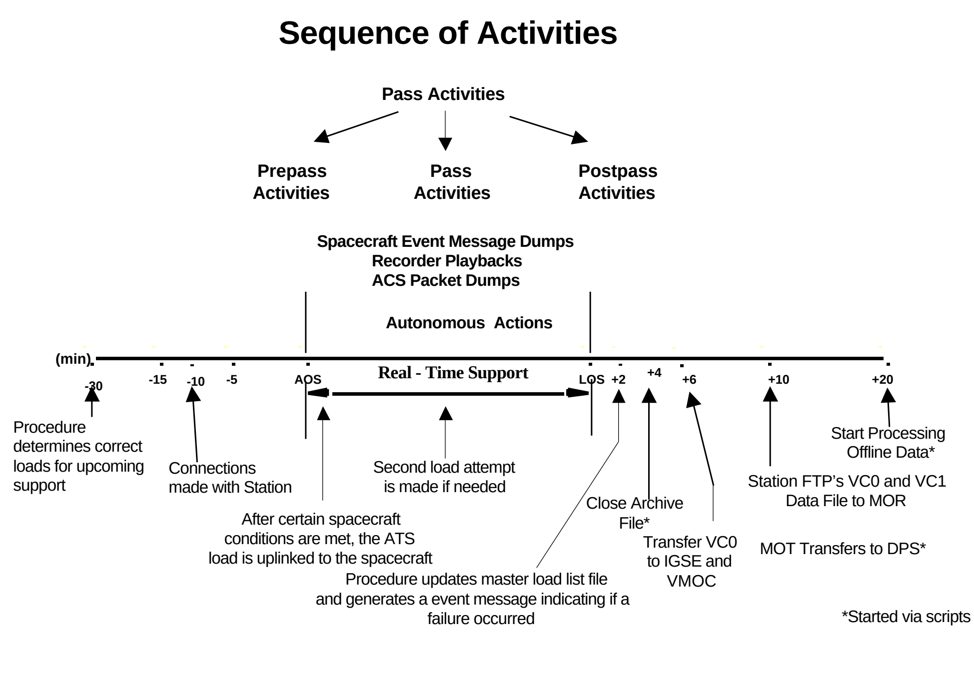

Figure 1: WIRE Auto-Load procedure activity time-line

waiting for the final verification which may never come if the process failed. If one of the two loads fails then commanding is stopped and the command buffer purged. An alert message is then written to the event log file so that the SERS will be able to notify the FOT of the failure.

At LOS+2 minutes the procedure performs standard LOS cleanup activities which also includes updating the 'loadlist' file to indicate the success or failure status of the loads just attempted. Event log file transfer to the SERS and other file transfers are performed via a Unix script.

Backup workstation functions:

The backup workstation is used after the pass is completed to process, or 'subset', the pre-recorded engineering housekeeping data. This data is FTP'd to the prime workstation after the pass is completed by the ground station. The data files are transferred to the backup workstation via a Unix script that continuously runs on the prime. The script periodically checks for the arrival of the data. When present, the files are then moved to the backup workstation.

3. "Auto Subset" Procedure

This procedure runs on the backup workstation and performs the subsetting. It autonomously runs at LOS +20 minutes by reading in the station support schedule to get the AOS and LOS times of each pass. This twenty-minute wait exists to allow the station time to FTP the stored housekeeping data files to the prime workstation, and for the prime to transfer them to the backup. The procedure then looks for the presence of the files and begins configuring the backup workstation for subsetting. The backup workstation then generates the same products from the playback data as were generated during the real-time contact with the much smaller set of real-time data (i.e. event logs, attitude and orbit files, etc. are created). Transfer of post-playback data sets is performed in the same manner using several Unix scripts.

7. Auto-Commanding Testing

The first step in testing the auto-commanding procedure was performing tests with the internal command simulator (Table 1). These tests did not have any connections to the station or simulate failure scenarios. After the launch of the SWAS spacecraft, the procedure and all of its scripts were converted over from WIRE so they would operate on the SWAS mission. As of December 30th, 1998, preliminary testing was performed with the SWAS spacecraft. On two occasions, the procedure executed while the SWAS FOT monitored the procedure in real-time. On both supports, the procedure executed correctly and performed the verification. More testing will be needed before the procedure can be declared operationally ready. Below is a list of some of the testing that will be performed.

Table 1: Test Matrix

No.	Test Description:	Status:
1	Conduct procedure tests to eliminate procedure errors.	Complete
2	Convert procedures and scripts to operate for SWAS	Complete
3	Monitor procedure in real-time using the SWAS spacecraft	Open
4	Test and verify possible failure scenarios while monitoring the procedure in real-time	Open
5	Execute the procedure with real-time monitoring for SWAS	Open
6	Apply any enhancements and updates to the WIRE procedures and scripts.	Open

8. Summary

Because of the automation tools that the SMEX FOT incorporated into normal operations of SMEX spacecraft, the team size was reduced by approximately half from the original multi-mission team size. These reductions resulted in cost savings to every SMEX mission and especially helped those missions remain funded in their extended mission phase. All of the techniques that were implemented were done with common tools that are available to every control center. The only specialized platform that SMEX currently uses is the SERS system. The remainder of the automation is accomplished through UNIX scripts and STOL procedure that were developed by the SMEX FOT. The team is continuously looking at ways to further automate operations, not only to reduce cost, but also to reduce the risk of errors. The only area that has not been seriously examined for automation is the off-line analysis that each mission is required to perform. Some initial work has been done in this area, but the work is still labor intensive.